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STUDY OF PERSISTENT PHOTOCONDUCTIVITY IN SEMIMETALLIC
 $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb/InAs}$ QUANTUM WELLSL.C. Tsai,^a J.C. Fan,^a Y.F. Chen^{a,*} and Ikai Lo^b^aDepartment of Physics, National Taiwan University, Taipei, Taiwan, Republic of China^bDepartment of Physics, National Sun Yat-Sen University, Kaohsiung, Taiwan, Republic of China

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The “positive” persistent photoconductivity (PPC) and “negative” persistent photoconductivity (NPPC) have been observed in $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb/InAs}$ quantum wells. The decay kinetics of the PPC and NPPC effects can be well described by stretched-exponential functions and the activation energy of the thermally activated relaxation was obtained. Through the studies of the NPPC and PPC effects under various conditions, such as different temperature and different photon energy of excitation, we suggest that the NPPC and PPC effects are caused by two competing processes. At $T \leq 40$ K, the electrons in the InAs wells are excited into the valence band of the AlGaSb layer, the recovery to the original state is prohibited by the barrier due to interface band bending and hence NPPC effects occur. At $T \geq 140$ K, the photoexcited holes are trapped by the deep defects in the InAs well and the remaining electrons contribute to the observed PPC. For $40 \text{ K} < T < 140 \text{ K}$, these two mechanisms compete with each other. The previously proposed model that describes the NPPC resulting from the capture of the photoexcited electrons by the DX-like deep donors in AlGaSb fails to explain our observation here. © 1998 Elsevier Science Ltd. All rights reserved

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$\text{Al}_x\text{Ga}_{1-x}\text{Sb/InAs}$ quantum wells have been studied recently with great interest due to their potential in high-speed electronic devices and infrared detector applications. In addition to engineering applications, many unusual physical phenomena have recently been observed, such as the negative persistent photoconductivity (NPPC) effect [1–3], the magnetic-field-induced semimetal-to-semiconductor transition [4, 5], the unexpected electron accumulation in the InAs well [1] and intrinsic excitonic ground state [6]. These phenomena arise from the unique band structure of $\text{Al}_x\text{Ga}_{1-x}\text{Sb/InAs}$, in which the band alignment can be tuned from a semiconducting phase to a semimetallic phase by changing either the Al composition or the InAs layer thickness with two-dimensional (2D) electrons in

the InAs well and 2D holes in the AlGaSb barriers. For example, this quantum well shows a semiconducting property when $x > 0.3$ or a semimetallic property when $x < 0.3$ [7].

Conventional persistent photoconductivity (PPC) is characterized by the increase of the free-carrier concentration after illumination which persists after the termination of the photoexcitation. Conversely, the opposite effect of NPPC is characterized by a decrease of the free-carrier concentration, instead of an increase after illumination. PPC has been observed in many important semiconductors and extensive work in this area has led to the understanding of carrier storage and the metastability of impurities [8–11]. Recently, NPPC has also been observed in *III–V* semiconductor heterostructures [12–14]. For the AlGaSb/InAs system, the NPPC effect has been studied by Shubnikov–de Haas (SdH) measurements [1, 3] and far-infrared (FIR)

* Corresponding author.

magneto-optical spectroscopy [2] at low temperature. Based on rather limited experimental results, it was previously proposed that the NPPC effect arises from the recombination of photoexcited holes in the AlGaSb layer with electrons in the InAs well and the capture of the photoexcited electrons by the DX-like deep donors in AlGaSb [1–3]. However, the nature of the deep levels in the AlGaSb layer and their role in the NPPC effect, have not been fully resolved. In this article we report on a detailed study of the persistent photoconductivity effect. Both the PPC and NPPC can be observed depending on the experimental condition. We point out that the previous model fails to interpret our observation. Here, a new mechanism is proposed to explain all our results as well as published reports.

The studied sample consists of a 150 Å GaSb cap, a 150 Å $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}$ barrier layer, a 150 Å InAs well layer, another $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}$ barrier of 9000 Å thickness and an AlSb/GaSb superlattice buffer layer, grown on semi-insulating GaAs substrate by molecular beam epitaxy. According to the previous result [7], our sample studied here has a semimetallic property. In the semimetallic phase, the valence band edge of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}$ lies above the conduction-band edge of InAs and electrons transfer from the $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}$ valence band to the InAs conduction band, leaving holes in the $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}$ layer. Using the linear interpolation of the corresponding values of bulk AlSb and GaSb for the energy gap, the theoretical result of the energy gap at 0 K for $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}$ and InAs is about 0.97 eV and 0.43 eV, respectively.

For the photoconductivity measurements, the ohmic contacts were formed by Indium. The samples was attached to a copper sample holder and placed inside a closed-cycle He refrigerator, with care to ensure good thermal contact yet electrical isolation. With a RMC Series 4000 thermometer/controller, the temperature of the cold finger could range from 12 K to 300 K. The data obtained at different conditions were taken in such a way that the system was always allowed to warm up to 300 K and relax to equilibrium after each measurement, then cool down in darkness to the desired temperature of measurements. This is to ensure that each set of data has the same initial condition. Light beams with different wavelengths coming from a halogen lamp dispersed by a monochromator with appropriate filters were used as the pumping sources. A bias of 0.2 V was supplied and the conductivity was measured by a Keithley 236 source-measure unit.

First, let us consider the dependence of NPPC behavior on the photon energy of the pumping source. As shown in Fig. 1, we find that after illumination, the conductivity decreases suddenly and increases rapidly after illumination is turned off and then slowly recovers

Fig. 1. The negative persistent photoconductivity (NPPC) curves at different pumping energies in an $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}/\text{InAs}$ quantum well at 16 K.

to the original dark value. These phenomena are a clear signature of a NPPC effect. In order to make sure that the reduced conductivity after illumination is caused by the reduction of electron concentration in the InAs well, we perform the SdH measurement as shown in Fig. 2. We

Fig. 2. The SdH measurements (insert) for the $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}/\text{InAs}$ quantum well with different illumination times and their fast Fourier transformation (FFT) spectra. The illumination was performed by a red light emitting diode.

can clearly see that after illumination, the peak positions of the SdH oscillations move to lower magnetic fields, indicating that the electron density decreases. Besides, the amplitude of the SdH oscillations is rather insensitive to illumination, which implies that the mobility of conducting carriers does not change with illumination. Note that NPPC at 16 K can still be observed even though the photon energy is as small as 0.2 eV. Previously, it was proposed that the main origin of NPPC effect is due to the recombination of photoexcited holes in the AlGaSb barrier and holes in InAs well and the capture of photoexcited electrons by the ionized deep donors in the $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}$ layer [1]. Our result clearly can rule out the possibility of this existing model as the underlying mechanism of the NPPC in the AlGaSb/InAs system, because in our experiment the pumping energy is not large enough to create electron–hole pairs in the $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}$ layer. Moreover, a direct excitation of electrons from the InAs well through the AlGaSb conduction band and capture by the ionized deep donors in the AlGaSb layer [2] can also be excluded.

To further explore the origin of the NPPC phenomena, we investigate the temperature dependence. Here the pumping energy is fixed at 0.69 eV, which is the approximate peak position of the photoresponse vs pumping photon energy. The NPPC decay curves for different temperatures are shown in Fig. 3. The “negative” PPC effect can be clearly observed in Figs 3(a)–(d) and Figs 3(h)–(k) show the “positive” PPC effect. Between these two regions, Figs 3(e)–(g) show the competition of the NPPC and PPC effects.

For Figs 3(a)–(c) and Figs 3(h)–(k), after the illumination is turned off, the recovery of the conductivity to the original dark value does not follow an exponential function. Instead, the decay kinetics of the NPPC or PPC can be described by a stretched exponential-function [15, 16],

$$I(t) = I(0) \exp[-(t/\tau)^\beta], \quad (1)$$

where $I(0)$ is the PPC(NPPC) build up level at the moment of light excitation being removed, τ is the PPC(NPPC) decay time constant and β is the decay exponent. From the fitted curves, we can obtain the exponential parameters τ and β for different temperatures. It is found that τ is thermally activated and can be described by the expression

$$\tau = \tau_0 \exp[E_{\text{rec}}/kT], \quad (2)$$

where E_{rec} is the activation barrier height and k is the Boltzmann constant. The potential barrier E_{rec} obtained from the NPPC effect and PPC effect are about 4.2 meV and 320 meV, respectively. Previously,

Fig. 3. The persistent photoconductivity curves at different temperatures in an $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}/\text{InAs}$ quantum well. The pumping energy is fixed at 0.69 eV.

stretched exponential relaxation has been observed in many materials [15–18]. It can be used to describe a decay process that does not have a constant decay rate. Particularly, if the decay rate decreases with time following a power law, the stretched exponential function can be easily obtained [15].

In order to look for the possible mechanism to interpret the observed persistent photoconductivity, let us first illustrate the band structure of the semimetallic $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}/\text{InAs}$ quantum well, as shown in Fig. 4. If we use a linear interpolation to estimate the band alignment of the studied sample [19], we obtain that the conduction band edge of InAs well is about 68 meV below the valence band edge of the AlGaSb layer. From the results obtained above, we propose that for $T \leq 40$ K (Figs 3(a)–(c)), electrons in the conduction band and/or valence band of the InAs layer were pumped into the valence band of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}$ illumination and the density of conducting 2D electrons in the InAs well decreases. After the photoexcitation is terminated, the photoexcited electrons in the AlGaSb layer have little possibility to return to the InAs layer because their kinetic energies are not large enough to overcome the interface band bending

Fig. 4. The schematic diagram of the semimetallic band alignment of the $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}/\text{InAs}$ quantum well.

and the NPPC can be observed. Our proposed model can resolve the difficulties that occur in the previous model. Because the energy difference between the conduction-band edge of InAs well and the valence-band edge of the AlGaSb layer is small, we thus only need a small photon energy to create the NPPC effect. In addition, because the interface band bending is also a small value, the NPPC can only be observed at low temperature. Furthermore, the interface band bending increases as electrons transfer from the AlGaSb to the InAs layer. As a result, the decay rate gradually decreases and it leads to the observed nonexponential curve. When temperature increases above 100 K, most electrons pumped into the valence band of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}$ layer return to the InAs layer and thus the NPPC disappears. Under this condition, the photoconduction is dominated by the creation of electron-hole pairs in the InAs well. We assume that the photoexcited holes are trapped by deep defects, which generate a local potential that effectively traps the holes and spatially separates the photoexcited electrons and holes. Thus, the excess photoexcited electrons contribute to the observed positive photoconductivity. As the pumping light is turned off, the recombination of photoexcited electrons and holes is prevented by the local potential and thus the PPC is observed. The probability for the trapped holes to overcome the capture barrier and to recombine with conduction electrons increases with increasing temperature. Thus, the relaxation time of the PPC decreases with increasing temperature as observed in Figs 3(h)–(k). The activation energy obtained from the PPC effect indicates that the capture barrier of deep defects is about 320 meV.

In conclusion, we have observed the NPPC and PPC effects in $\text{Al}_{0.2}\text{Ga}_{0.8}\text{Sb}/\text{InAs}$ quantum wells. Analyzing the studies of the NPPC and PPC effects under different conditions, we point out that the previously proposed model, which attributes the NPPC effect to the capture of

photoexcited electrons by the DX-like deep donors in AlGaSb layer, fails to explain our observed behavior. We suggest that the NPPC and PPC effect arise from two competing processes. At low temperature ($T \leq 40$ K), the process of the transfer of photoexcited electrons from the InAs well to the valence band of the AlGaSb layer dominates and the NPPC occurs. At high temperatures ($T \geq 100$ K), the creation of electron-hole pairs in the InAs well is more important and it results in the PPC effect.

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REFERENCES

1. Tuttle, G., Kroemer, H. and English, J.H., *J. Appl. Phys.*, **65**, 1989, 5239; Hopkins, P.F., Rimberg, A.J., Westervelt, R.M., Tuttle, G. and Kroemer, H., *Appl. Phys. Lett.*, **58**, 1991, 1428.
2. Lo, Ikai, Mitchel, W.C., Manasreh, M.O., Stutz, C.E. and Evans, K.R., *Appl. Phys. Lett.*, **60**, 1992, 751; Cheng, J.P., Lo, Ikai and Mitchel, W.C., *J. Appl. Phys.*, **76**, 1994, 667.
3. Lo, Ikai, Mitchel, W.C., Elhamri, S., Newrock, R.S. and Kaspi, R., *Appl. Phys. Lett.*, **65**, 1994, 1024; *Phys. Rev.*, **B40**, 1989, 5852.
4. Smith III, T.P., Munekata, H., Chang, L.L., Fang, F.F. and Esaki, L., *Surf. Sci.*, **196**, 1988, 687.
5. Lo, Ikai, Mitchel, W.C. and Cheng, J.P., *Phys. Rev.*, **B48**, 1993, 9118.
6. Cheng, J.P., Kono, J., McCombe, B.D., Lo, I., Mitchel, W.C. and Stutz, C.E., *Phys. Rev. Lett.*, **74**, 1995, 450.
7. Munekata, H., Maan, J.C., Chang, L.L. and Esaki, L., *J. Vac. Sci. Technol.*, **B5**, 1987, 809.
8. Lang, D.V. and Lang, R.A., *Phys. Rev. Lett.*, **39**, 1977, 635.
9. Queisser, H.J. and Theodorou, D.E., *Phys. Rev. Lett.*, **43**, 1979, 401.
10. Dissanayake, A.S., Lin, J.Y. and Jiang, H.X., *Phys. Rev.*, **B48**, 1993, 8145.
11. Chen, H.M., Chen, Y.F., Lee, M.C. and Feng, M.S., *Phys. Rev.*, **B56**, 1997, 6942.
12. Chou, M.J., Tsui, D.C. and Weimann, G., *Appl. Phys. Lett.*, **47**, 1985, 609.
13. Kukushkin, I.V., von Klitzing, K., Ploog, K., Kirpichev, V.E. and Shepel, B.N., *Phys. Rev.*, **B40**, 1989, 4179.
14. Powell, A.L., Button, C.C., Roberts, J.S., Rockett, P.I., Grimmeiss, H.G. and Petterson, H., *Phys. Rev. Lett.*, **67**, 1991, 3010.
15. Kakalios, J., Street, R.A. and Jackson, W.B., *Phys. Rev. Lett.*, **59**, 1987, 1037.

16. Chen, Y.F., Huang, S.F. and Chen, W.S., *Phys. Rev.*, **B44**, 1991, 12748.
17. Jiang, H.X. and Lin, J.Y., *Phys. Rev. Lett.*, **57**, 1990, 873.
18. Chen, H.M., Chen, Y.F., Lee, M.C. and Feng, M.S., *J. Appl. Phys.*, **82**, 1997, 899.
19. Lo, Ikai, Mitchel, W.C. and Cheng, J.P., *Phys. Rev.*, **B50**, 1994, 5316.